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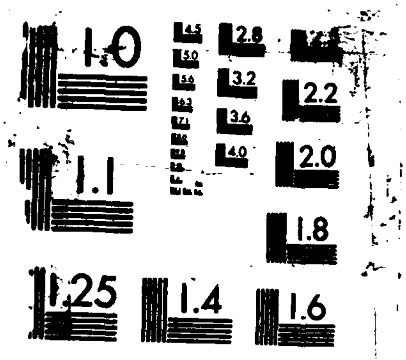

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EFFECTS OF SULFUR CONTENT ON THE PLAIN STRAIN FRACTURE TOUGHNESS OF INERTIA WELDS IN 4340 STEEL

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PROCESSING TECHNOLOGY DIVISION

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ABSTRACT

The plain strain fracture toughness of post-weld, reheat treated inertia welds in two heats of AISI 4340 steel of equivalent tensile properties, but different sulfur concentrations, was determined. The adverse reorientation of elongated sulfide inclusions in both heats, resultant from the forging stage of the welding cycle, caused reductions in ductility and toughness that were not remedied by reheat treatments. The percent elongation of inertia welded joints was found to be no greater than 50% that of the parent metal even at the lowest sulfur concentrations of 0.004%. K_{IC} data was less significantly effected by sulfur concentration and fiber morphology. In addition, the fracture toughness of these welds in 0.014% S material, as determined from sharp notch fatigue cracked specimens, was actually found to be greater than that of welds in 0.004% S material. This was due to the more tortuous fracture path and the resultant greater fracture surface formed during crack propagation. L-C rather than L-R crack plane orientations for K_{IC} specimens produced more reliable mechanical property data due to the more uniform microstructure ahead of the crack front. The magnitude of base metal elongation, especially in the short transverse orientation, is proposed as an index of inertia/friction weldability.

INTRODUCTION

Inertia welding, a form of friction welding, is a solid state joining process that produces bonding using the heat developed between two surfaces during mechanically induced rubbing motion. The inertia welding cycle can be divided into two stages: the friction stage, and the upsetting or forging stage. Welding heat is developed during the first stage, and the weld is consolidated and cooled during the second stage. In principle, almost any metal that can be hot forged and is unsuitable for dry bearing applications can be inertia welded.[1]

It is well known that for any steel worked principally in one direction, the mechanical properties, especially ductility, in the direction of working are different from those in the perpendicular or short transverse direction.[2,3] On application of forging pressure during an inertia weld, metal is forced out in a radial direction normal to the forging direction. Consequently, any inclusions in the weld zone initially oriented parallel to this major working direction are reoriented into a direction normal to this axis within the bond zone during the forging stage. Short transverse base metal properties should, therefore, be expected across inertia welded joints.

Although the weldability,[4] strength,[5] and fatigue life[6,7] of carbon and low alloy steel weldments joined by inertia and similar welding processes (e.g., flash and friction) have been good, various measures of ductility for these joints have been poor. Not unexpectedly, this was also attributed to the adverse reorientation and insufficient dissemination of non-metallic inclusions in the weld zone.* Some investigators,[8,9] however, have found that a post-weld, reheat treatment of weldments could remedy these effects.

Welding and base metal parameters have previously been related to changes in the size, shape, and profile of inertia and similar welded joints. However, comparable effects on the metallurgical structure and particularly fracture toughness properties of these joints have not been reported. Research** on friction welded austenitic stainless steels has shown a direct relationship of the effect of sulfur content on Charpy energy; however, if sulfur concentrations are kept below 0.025% the effect of friction welding on ductility is slight. Others[10] have gone one step further in quantifying that the observed ductility drop was highly localized by determining that impact properties returned to unaffected base metal levels within 0.20" of the bond line in flash welds.

*OKITA, K. *Studies on Friction Welding of SUS 304 Austenitic Stainless (Report 1).* Private communication, 1984.

**OKITA, K. *Effects of Sulfur Content of Base Metal on the Friction Weldability of SUS 304 Austenitic Steels.* Private communication, 1984.

1. *Welding Handbook, Vol. 3, Resistance and Solid State Welding and Other Joining Processes.* 7th Ed., W. H. Kearns, ed., American Welding Society, Miami, Florida, 1980, p. 244.
2. PORTER, L.F. *Lamellar Tearing in Plate Steels (A Literature Survey).* AISI, August 1975.
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10. MUSCH, H., LANGER, J., DUREN, C., and LUGGER, H. *Flash Butt Welding for Large Diameter Pipes.* Proc. 13th Annual Offshore Technology Conference, Houston, Texas, 4-7 May 1981, v. 3, Paper 4103, p. 327-340.

In this report, the fracture toughness properties of inertia welded 4340 steel, post-weld reheat treated to attain high strength levels, will be presented. It is believed that fracture toughness data can be used for the design and inspection of welded structures whenever it is necessary to detect flaws of a critical size. The work presented will show the effects of sulfur content, at 0.004 and 0.014% levels, on the toughness properties of inertia welds. The use of percent elongation as an inexpensive index of inertia/friction weldability will be justified.

EXPERIMENTAL

Seamless tubing (6.25" outer diameter with a wall thickness of 0.5") from two electric furnace melted heats of AISI 4340 steel was inertia welded. The chemical compositions of the two heats are shown in Table 1. Carbon and sulfur were measured by combustion techniques; all other elements were analyzed by emission spectroscopy.

Table 1. CHEMICAL COMPOSITIONS OF THE TWO HEATS TESTED

	C	S	Mn	P	Si	Ni	Cr	Mo	Cu	V
Heat #1	0.38	0.004	0.71	0.012	0.22	1.78	0.78	0.23	0.07	0.006
Heat #2	0.41	0.014	0.71	0.014	0.25	1.82	0.85	0.25	0.15	0.016
Typical 4340	0.38-0.43	<0.04	0.60-0.80	<0.035	0.20-0.30	1.65-2.00	0.70-0.90	0.20-0.30	-	-

All welds were fabricated in accordance with MIL-STD-1252 for type I, class B welds. A flywheel speed of 1225 rpm and a forging pressure of 3400 psi were used. Workpieces were heat treated, prior to and after welding, according to the process schedule shown in Figure 1.

Type TR-3A, 0.252" diameter, threaded, round tensile specimens and type CV-2, 0.394" X 0.394" X 2.165" Charpy V-notched specimens were machined from each quadrant of the welded section. Flood coolant conditions were used to prevent burning. The weld line was located in the center of each specimen. Notches were machined in the Charpy specimens to provide both L-C and L-R crack plane orientations (Figure 2). The Charpy specimens were then precracked by tensile fatigue loading. Fracture toughness data were obtained in slow bending at room temperature, in accordance with ASTM E 399, and fracture surfaces were evaluated by SEM and optical microscopy techniques.

RESULTS

Mechanical property data, including tensile and fracture toughness data, for the base metal and welds of the 0.004 and 0.014% sulfur heats are shown in Table 2. SEM examination using EDAX confirmed the presence of MnS stringers on the fracture surface of weld tensile specimens (Figure 3). Fracture surfaces of K_{IC} specimens for both heats and crack plane orientations are shown in Figures 4 and 5.

Distance from the crack tip to the weld centerline was measured in the K_{IC} specimens as shown in Figure 6. Fracture toughness data for each specimen in the L-R orientation are plotted vs. distance from the weld centerline in Figure 7 for both heats of material.

Table 2. MECHANICAL PROPERTIES OF BASE METAL AND WELD JOINTS FOR TWO HEATS OF 4340 STEEL

	Yield Strength 0.2% Offset (ksi)	Ultimate Tensile Strength (ksi)	Percent Elongation	K_{IC} @ $68^{o}F$ ($ksi\sqrt{in.}$)		Hardness R_c
				LC	LR	
Heat #1						
Base Metal	212.3 (2.5)*	255.7 (0.9)	13.3 (0.42)	73.9 (2.3)	71.6 (3.6)	49.7 (0.19)
Weld	210.8 (1.7)	247.5 (1.3)	6.8 (0.79)	59.0 (1.3)	61.5 (4.1)	49.2 (0.1)
Heat #2						
Base Metal	215.6 (3.04)	252.0 (2.95)	12.7 (0.40)	71.3 (4.9)	73.3 (4.8)	49.7 (0.34)
Weld	213.52 (0.79)	246.2 (4.67)	4.31 (0.26)	63.4 (1.33)	67.65 (6.05)	49.0 (0.29)

*Standard deviation

DISCUSSION

The ultimate and yield strengths for the base metal and weld are nearly identical for both heats of material. The effects of small differences in sulfur content on weld joint ductility are therefore notable. As expected, the percent elongation across the weld of the low sulfur material was slightly higher than that of the higher sulfur material, although, in both cases, elongation values for the welds were much less than the base metal values. The magnitude of this difference (66% for the higher sulfur material) was not expected, but others[9] have shown that short transverse (through thickness) ductility decreased more for higher sulfur contents than long transverse ductility.

Fracture toughness data also showed a slight difference between the two base metals but failed to parallel the dramatic reduction in weld properties as reflected by the percent elongation data. More importantly, the fracture toughness of the higher sulfur weldment was in fact greater than that of the low sulfur weldment at the weld centerline. This phenomenon can only be explained by examining the resultant fracture surfaces (Figures 4 and 5). Here, the fracture path in the high sulfur material, more tortuous than that in the low sulfur material, causes a greater amount of new surface area to be created, thereby requiring more energy for crack propagation and resulting in the higher observed toughness values.

Fracture toughness data allow us to predict critical flaw sizes so that nondestructive inspection techniques of a suitable sensitivity may be selected. The data presented in this work, however, show that expensive K_{IC} tests are not as reliable as simple tensile tests in flagging potential problems that could be process, as well as metallurgically, related. Although 0.014% sulfur is considered low, a more dramatic difference in fracture toughness between the weld and parent metal and between the two base metals themselves was anticipated.

Even though its value was low, the standard deviation in K_{IC} data for the L-R welded fracture toughness specimens was greater than that for the L-C specimens.

The presumed reason is the sensitivity of the fracture process to the depth or location of the precrack with respect to the through wall thickness orientation and, therefore, the variation in fiber morphology in this direction.

One accepted practice, to prevent sulfides from becoming excessively elongated during primary forming, is to alter their composition and shape through rare earth additions. Weld toughness properties are similarly expected to increase with this approach to sulfide shape control. However, predictions by Speich[11] indicate that this shape control effect may be slight at higher strength levels.

CONCLUSIONS

The relative degradation of short transverse base metal properties should be expected across inertia welded joints. The reason for this is the adverse reorientation of non-metallic inclusions in the weld zone. These massive effects could not be expected to be eliminated by typical post-weld reheat treatments.

Although the tensile values of welded joints can be restored to nearly base metal values by post-weld reheat treatment, the percent elongation is expected to be no greater than 50% that of the parent metal in low alloy steels, even with sulfur concentrations less than 0.015%.

The differentials in the plain strain fracture toughness values between base metal and weld zone were much less than elongation values.

The fracture toughness of inertia welds in 0.014% sulfur material was higher than that of 0.004% sulfur material at the same strength level. This was attributed to the more tortuous fracture path followed for the higher sulfur material.

Comparative fracture toughness values (both average and standard deviation) in the L-C orientation provide more reliable data than those in the L-R orientation. This is due to the more uniform fiber morphology ahead of the crack front for this orientation.

Base metal percent elongation in the short transverse direction may be used as an index of friction/inertia weldability, and is a useful quality control tool for flagging material as well as welding process variations.

11. SPEICH, G.R., and SPITZIG, W.A. *Effect of Volume Fraction and Shape of Sulfide Incusions on Through-Thickness Ductility and Impact Energy of High Strength 4340 Plate Steels.* Metall. Trans. A, v. 13A, December 1982, p. 2239-2258.

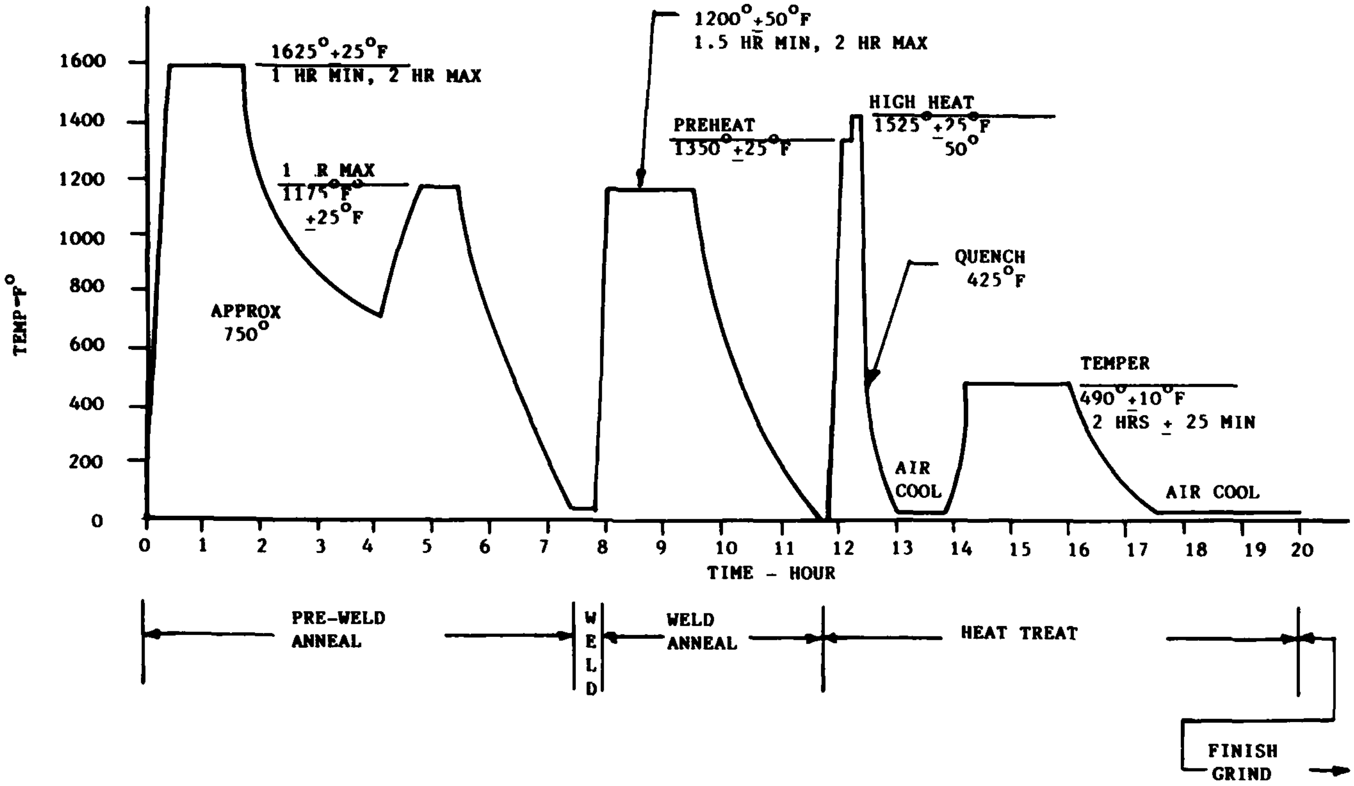


Figure 1. Heat treatment schedule.

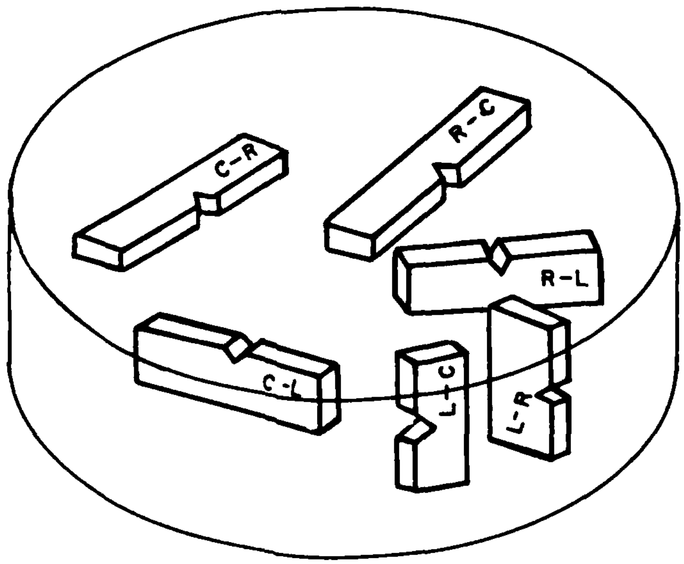


Figure 2. Crack plane orientation identification code.

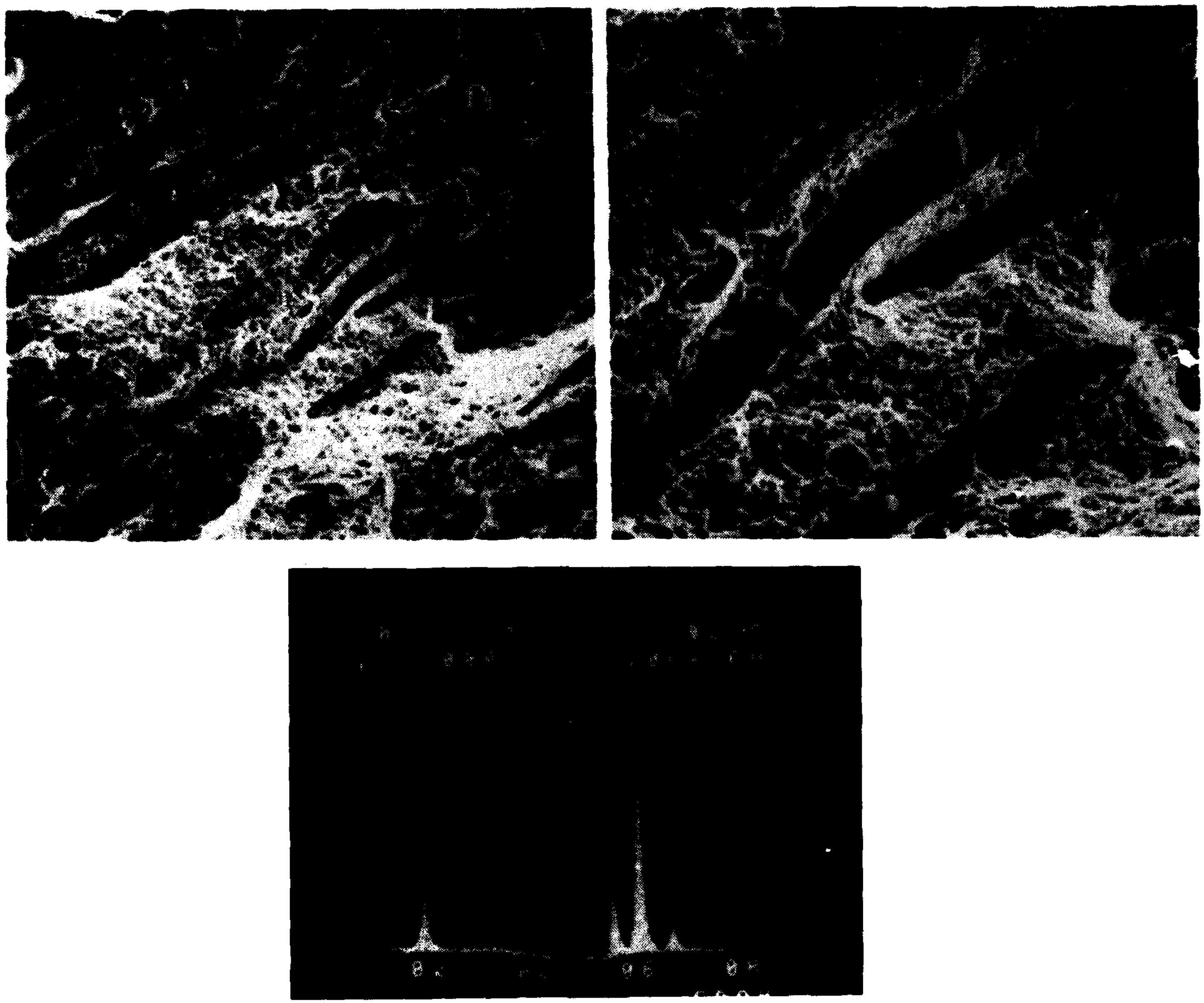
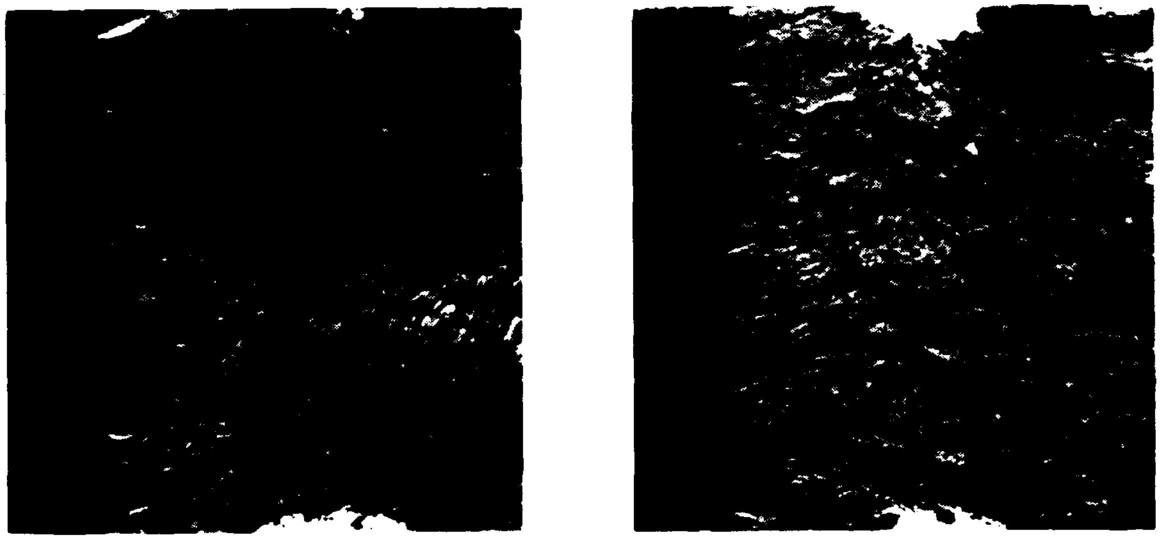


Figure 3. MnS stringers found on tensile specimens by SEM (150X and 500X). EDAX analysis confirms presence of MnS stringers (Heat 2).

(a) (b)

Figure 4. Fracture surface of K_{IC} specimens taken through the weld in the 0.004% sulfur material: (a) L-C, (b) L-R (7X).



(a) (b)

Figure 5. Fracture surfaces of K_{IC} specimens taken through the weld in the 0.014% sulfur material: (a) L-C, (b) L-R (7X).

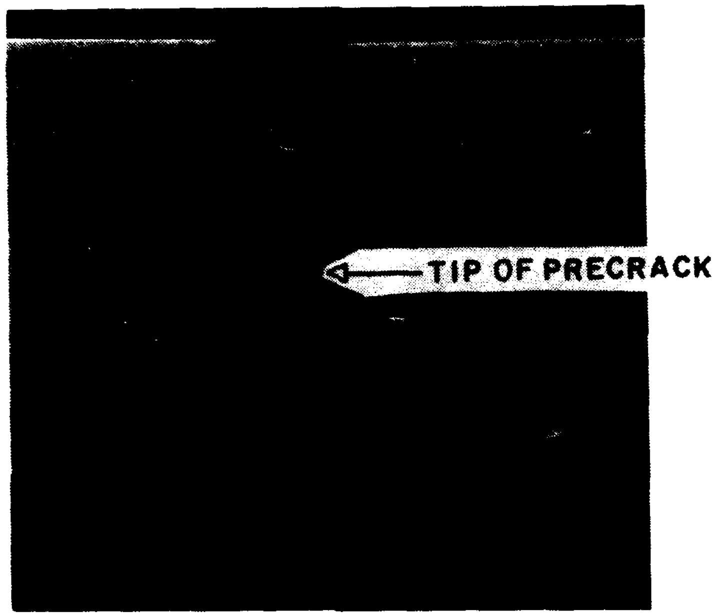


Figure 6. View of a fracture toughness specimen after testing. The distance from the weld centerline to the crack tip was measured for each specimen.

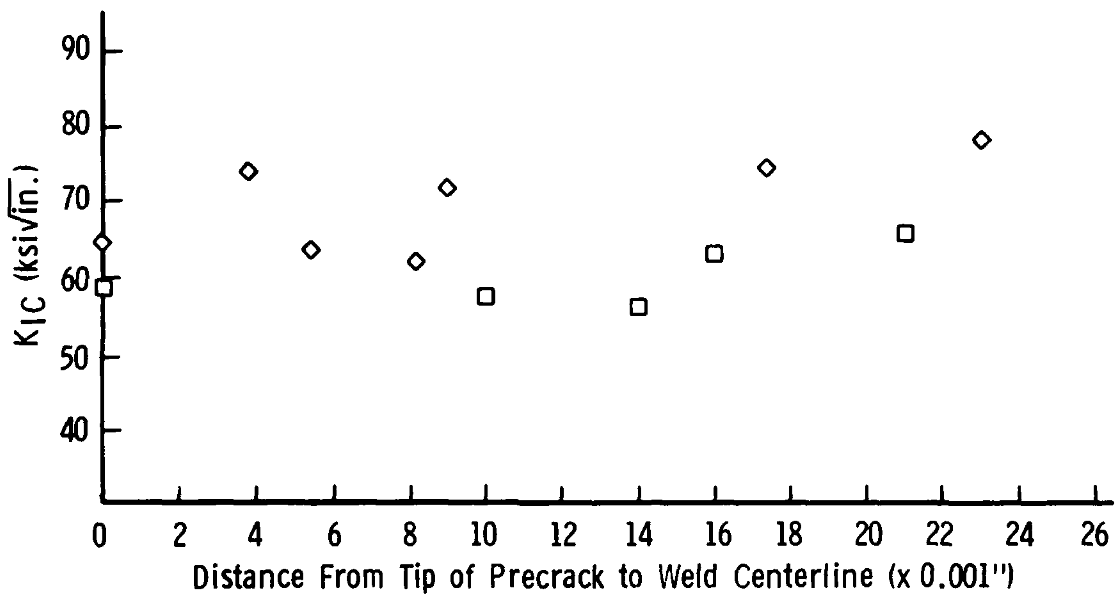


Figure 7. Fracture toughness values plotted vs. the distance from the tip of the precrack to the weld centerline for 0.004% sulfur (□) and 0.014% sulfur (◇) materials.

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Key Words

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Welding
Fracture

Technical Report MTL TR 87-53, September 1987, 11 pp - illus-table, D/A Project: 1L263102D077, Agency Accession: DA 30 3398.

The plain strain fracture toughness of post-weld, reheat treated inertia welds in two heats of AISI 4340 steel of equivalent tensile properties, but different sulfur concentrations, was determined. The adverse reorientation of elongated sulfide inclusions in both heats, resultant from the forging stage of the welding cycle, caused reductions in ductility and toughness that were not remedied by reheat treatments. The percent elongation of inertia welded joints was found to be no greater than 50% that of the parent metal even at the lowest sulfur concentrations of 0.004%. K_{IC} data was less significantly effected by sulfur concentration and fiber morphology. In addition, the fracture toughness of these welds in 0.014% S material, as determined from sharp notch fatigue cracked specimens, was actually found to be greater than that of welds in 0.004% S material. This was due to the more tortuous fracture path and the resultant greater fracture surface formed during crack propagation. L-C rather than L-R crack plane orientations for K_{IC} specimens produced more reliable mechanical property data due to the more uniform microstructure ahead of the crack front. The magnitude of base metal elongation, especially in the short transverse orientation, is proposed as an index of inertia/friction weldability.

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EFFECTS OF SULFUR CONTENT ON THE PLAIN STRAIN FRACTURE TOUGHNESS OF INERTIA WELDS IN 4340 STEEL - William S. Ricci, Eric B. Kula, and James Colgate

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